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U.S. PATENT APPLICATION

for

MULTI FREQUENCY MAGNETIC DIPOLE ANTENNA STRUCTURES AND METHODS OF REUSING THE VOLUME OF AN ANTENNA

Inventors: Laurent Desclos
Gregory Poilasne
Jeff Shamblin
Sebastian Rowson

Attorneys:
FOLEY & LARDNER
321 North Clark Street
Suite 2800
Chicago, IL 60610-4764
Telephone: 312.832.4500
Facsimile: 312.932.4700

Multi Frequency Magnetic Dipole Antenna Structur s and Methods of Reusing the Volume of an Antenna

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of co-pending application Serial No. 10/253,016 filed September 23, 2002, which is a continuation of application Serial No. 09/892,928 filed June 26, 2001, now U.S. Patent No. 6,456,243, the disclosure of which is incorporated herein by reference.

[0002] This application relates to Patent No. 6,323,810, titled "Multimode Grounded Finger Patch Antenna" by Gregory Poilasne et al., owned by the assignee of this application and incorporated herein by reference.

[0003] This application also relates to co-pending application Serial No. 09/781,779, titled "Spiral Sheet Antenna Structure and Method" by Eli Yablonovitch et al., owned by the assignee of this application and incorporated herein by reference.

[0004] This application also relates to co-pending application Serial No. 10/076,922 titled "Multifrequency Magnetic Dipole Antenna Structures for Very Low Profile Antenna Applications" by Gregory Poilasne et al., owned by the assignee of this application and incorporated herein by reference.

FIELD OF THE INVENTION

[0005] The present invention relates generally to the field of wireless communications, and particularly to the design of an antenna.

BACKGROUND OF THE INVENTION

[0006] An antenna is an electrical conductor or array of conductors that radiates (transmits and/or receives) electromagnetic waves. Electromagnetic waves are often referred to as radio waves. Most antennas are resonant devices, which operate efficiently over a relatively narrow frequency band. An antenna must be tuned to the same frequency band that the radio system operates in, otherwise reception and/or transmission will be impaired. Small antennas are required for portable wireless communications. With classical antenna structures, a certain physical volume is required to produce a resonant antenna structure at a particular radio frequency and with a particular bandwidth. Thus, traditionally bandwidth and frequency requirements dictated the volume of an antenna.

[0007] The bandwidth of an antenna refers to the range of frequencies over which the antenna can operate satisfactorily. It is usually defined by impedance mismatch but it can also be defined by pattern features such as gain, beamwidth, etc.. Antenna designers quickly assess the feasibility of an antenna requirement by expressing the required bandwidth as a percentage of the center frequency of the band. Different types of antennas have different bandwidth limitations. Normally, a fairly large volume is required if a large bandwidth is desired. Accordingly, the present invention addresses the needs of small compact antenna with wide bandwidth. The present invention provides a versatile antenna design that resonates at more than one frequency, that is it is multiresonant, and that may be adapted to a variety of packaging configurations.

[0008] A magnetic dipole antenna is a loop antenna that radiates electromagnetic waves in response to current circulating through the loop. The antenna contains one or more elements. Elements are the conductive parts of an antenna system that determine the antenna's electromagnetic characteristics. The element of an magnetic dipole antenna is designed so that it resonates at a predetermined

frequency as required by the application for which it is being used. The antenna's resonant frequency is dependant on the capactive and inductive properties of the antenna elements. The capacitive and inductive properties of the antenna elements are dictated by the dimensions of the antenna elements and their interelations.

[0009] The radiated electromagnetic wave from an antenna is characterized by the complex vector E x H in which E is the electric field and H is the magnetic field. Polarization describes the orientation of the radiated wave's electric field. For maximum performance, polarization must be matched to the orientation of the radiated field to receive the maximum field intensity of the electromagnetic wave. If it is not oriented properly, a portion of the signal is lost, known as polarization loss. Dependent on the antenna type, it is possible to radiate linear, elliptical, and circular signals. In linear polarization the electric field vector lies on a straight line that is either vertical (vertical polarization), horizontal (horizontal polarization) or on a 45 degree angle (slant polarization). If the radiating elements are dipoles, the polarization simply refers to how the elements are oriented or positioned. If the radiating elements are vertical, then the antenna has vertical polarization and if horizontal, it has horizontal polarization. In circular polarization two orthogonal linearly polarized waves of equal amplitude and 90 degrees out of phase are radiated simultaneously.

[0010] Magnetic dipole antennas can be designed with more than one antenna element. It is often desirable for an antenna to resonate at more than one frequency. For each desired frequency, an antenna element will be required. Different successive resonances occur at the frequencies f_1, f_2, f_i... f_n. These peaks correspond to the different electromagnetic modes excited inside the structure. The antenna can be designed so that the frequencies provide the antenna with a wide bandwidth of coverage by utilizing overlapping or nearly overlapping frequencies. However, antennas that have an wider bandwidth than a

monoresonant antenna often have a correspondingly increased size. Thus, there is a need in the art for a multiresonant antenna; wherein the individual antenna elements share volume within the antenna structure.

SUMMARY OF THE INVENTION

[0011] The present invention relates to antennas having small volumes in comparison to prior art antennas of a similar bandwidth and type. In the present invention, the antenna elements include both capacitive and inductive parts. Each element provides a frequency or band of frequencies to the antenna.

[0012] In a preferred embodiment, the basic antenna element comprises a substantially planar structure with a planar conductor and a pair of parallel elongated conductors, each having a first end electrically connected to the planar conductor. Additional elements may be coupled to the basic element in an array. In this way, individual antenna structures share common elements and volumes, thereby increasing the ratio of relative bandwidth to volume.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Figure 1 conceptually illustrates the antenna designs of the present invention.

[0014] Figure 2 illustrates the increased overall bandwidth achieved with a multiresonant antenna design.

[0015] Figure 3 is an equivalent circuit for a radiating structure.

[0016] Figure 4 is an equivalent circuit for a multiresonant antenna structure.

[0017] Figure 5 illustrates a basic radiating structure utilized in an embodiment of the present invention.

[0018] Figure 6 illustrates a dual-mode antenna in accordance with an embodiment of the present invention.

[0019] Figure 7 illustrates a multimode antenna in accordance with another embodiment of the present invention.

[0020] Figure 8 illustrates an antenna in accordance with the present invention that is formed flat on a substrate.

[0021] Figure 9 illustrates an antenna in accordance with an embodiment of the present invention with returns for ground and a feed.

[0022] Figures 10A-10C illustrate the use of vias to provide feeds and shorts for an antenna in accordance with an embodiment of the present invention.

[0023] Figures 11A-11C illustrate a dual frequency antenna in accordance with an embodiment of the present invention with side-by-side elements.

[0024] Figure 12 illustrates a dual frequency antenna in accordance with an embodiment of the present invention with nested elements.

[0025] Figure 13 illustrates an antenna in accordance with an embodiment of the present invention similar to that of Fig. 12 with an additional capacitive element to provide an additional resonant frequency.

[0026] Figures 14A-14B illustrate a two-sided antenna in accordance with an embodiment of the present invention with three frequencies on one face of a substrate and a single frequency on the other face.

[0027] Figures 15A-15B illustrate an antenna in accordance with an embodiment of the present invention with conductors formed on the edge as well as the face of a substrate.

[0028] Figures 16A-16B illustrate a multifrequency planar antenna in accordance with an embodiment of the present invention on a primary substrate with an additional radiating element on a perpendicular secondary substrate.

[0029] Figures 17A-17B illustrate antennas in accordance with an embodiment of the present invention with multiple secondary substrates.

[0030] Figure 18 illustrates an antenna in accordance with an embodiment of the present invention with an extended radiating element.

[0031] Figure 19 illustrates an antenna in accordance with an embodiment of the present invention with a pair of extended radiating elements.

[0032] Figure 20 shows the antenna of Fig. 19 within an enclosure in accordance with an embodiment of the present invention.

[0033] Figure 21 illustrates an antenna similar to that of Fig. 19 with additional radiating elements on perpendicular secondary substrates in accordance with an embodiment of the present invention.

[0034] Figure 22 shows the antenna of Fig. 21 within an enclosure in accordance with an embodiment of the present invention.

[0035] Figure 23 illustrates an antenna structure in accordance with an embodiment of the present invention with two radiating elements at opposite ends of a substrate.

[0036] Figure 24 illustrates a laptop computer in accordance with an embodiment of the present invention with multiple radiating elements.

[0037] Figure 25 illustrates an antenna in accordance with an embodiment of the present invention printed on a substrate with a milled groove between the conductors.

[0038] Figure 26 illustrates a multifrequency antenna in accordance with an embodiment of the present invention with a plurality of milled grooves.

[0039] Figure 27 illustrates an alternative method of fabricating an antenna structure in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0040] The volume to bandwidth ratio is one of the most important constraints in modern antenna design. The physical volume of an antenna can place severe constraints on the design of small electronic devices. One approach to increasing

this ratio is to re-use the volume for different modes. Some designs already use this approach, even though the designs do not optimize the volume to bandwidth ratio. In these designs, two modes are generated using the same physical structure, although the modes do not use exactly the same volume. The current repartition of the two modes is different, but both modes nevertheless use a common portion of the total available volume of the antenna. This concept of utilizing the physical volume of the antenna for a plurality of antenna modes is illustrated generally by the Venn Diagram of Figure 1. The physical volume of the antenna ("V") has two radiating modes. The physical volume associated with the first mode is designated 'V_1', whereas that associated with the second mode is designated 'V_2'. It can be seen that a portion of the physical volume, designated '$V_{1,2}$', is common to both of the modes.

[0041] The concept of volume reuse and its frequency dependence are expressed with reference to "K law". The general K law is defined by the following:

$$\Delta f / f = K \bullet V / \lambda^3$$

wherein $\Delta f/f$ is the normalized frequency bandwidth, λ is the wavelength, and the term V represents the physical volume that will enclose the antenna. This volume so far has not been optimized and no discussion has been made on the real definition of this volume and the relation to the K factor.

[0042] In order to have a better understanding of the K law, different K factors are defined:

K_{modal} is defined by the mode volume V_i and the corresponding mode bandwidth:

$$\Delta f_i / f_i = K_{modal} \bullet V_i / \lambda_i^3$$

where i is the mode index.

K_{modal} is thus a constant related to the volume occupied by one electromagnetic mode.

$K_{effective}$ is defined by the union of the mode volumes V_1 U V_2 U..V_i and the cumulative bandwidth. It can be thought of as a cumulative K:

$$\sum_i \Delta f_i / f_i = K_{effective} \bullet (V_i \cup V_2 \cup ..V_i) / \lambda_C^3$$

where λ is the wavelength of the central frequency.

$K_{effective}$ is a constant related to the minimum volume occupied by the different excited modes taking into account the fact that the modes share a part of the volume. The different frequencies f_i must be very close in order to have nearly overlapping bandwidths.

$K_{physical}$ or $K_{observed}$ is defined by the physical volume 'V' of the antenna and the overall antenna bandwidth:

$$\Delta f / f = K_{physical} \bullet V / \lambda^3$$

[0043] $K_{physical}$ or $K_{observed}$ is the most important K factor since it takes into account the real physical parameters and the usable bandwidth. $K_{physical}$ is also referred to as $K_{observed}$ since it is the only K factor that can be calculated experimentally. In order to have the modes confined within the physical volume of the antenna, $K_{physical}$ must be lower than $K_{effective}$. However these K factors are often nearly equal. The best and ideal case is obtained when $K_{physical}$ is approximately equal to $K_{effective}$ and is also approximately equal to the smallest K_{modal}. It should be noted that confining the modes inside the antenna is important in order to have a well-isolated antenna.

[0044] One of the conclusions from the above calculations is that it is important to have the modes share as much volume as possible in order to have the different modes enclosed in the smallest volume possible. As previously discussed, the concept is illustrated in the Venn Diagram shown in Figure 1. Maximizing the number of modes while minimizing the volume of the antenna results in antennas that are multiresonant, yet are not much larger than a monoresonant antenna.

[0045] For a plurality of radiating modes i, Figure 2 shows the observed return loss of a multiresonant structure. Different successive resonances occur at the frequencies f_1, f_2, f_i... f_n. These peaks correspond to the different electromagnetic modes excited inside the structure. Figure 2 illustrates the relationship between the physical, or observed, K and the bandwidth over f_1 to f_n.

[0046] For a particular radiating mode with a resonant frequency at f_1, we can consider the equivalent simplified circuit L_1C_1 shown in Figure 3. By neglecting the resistance in the equivalent circuit, the bandwidth of the antenna is simply a function of the radiation resistance. The circuit of Figure 3 can be repeated to produce an equivalent circuit for a plurality of resonant frequencies.

[0047] Figure 4 illustrates a multimode antenna represented by a plurality of inductance(L)/capacitance(C) circuits. At the frequency f_1 only the circuit L_1C_1 is resonating. Physically, one part of the antenna structure resonates at each frequency within the covered spectrum. By utilizing antenna elements with overlapping resonance frequencies of f_1 to f_n, an antenna in accordance with the present invention can cover frequencies 1 to n. Again, neglecting real resistance of the structure, the bandwidth of each mode is a function of the radiation resistance.

[0048] As discussed above, in order to optimize the K factor, the antenna volume is reused for the different resonant modes. One embodiment of the present invention utilizes a capacitively loaded microstrip type of antenna as the basic radiating structure. Modifications of this basic structure will be subsequently described. In a highly preferred embodiment, the elements of the multimode antenna structures have closely spaced resonance frequencies.

[0049] Figure 5 illustrates a single-mode capacitively loaded antenna. If we assume that the structure in Figure 5 can be modeled as a L_1C_1 circuit, then C_1 is the capacitance across gap g. Inductance L_1 is mainly contributed by the loop designated by the numeral 2. The gap g is much smaller than the overall thickness

of the antenna. The presence of only one LC circuit limits this antenna design to operating at a single frequency.

[0050] Figure 6 illustrates a dual-mode antenna based on the same principles as the antenna shown in Figure 5. Here, a second antenna element is placed inside the first antenna element described above. This allows tuning one to a certain frequency f_1 and the other one to another frequency f_2. The two antennas have a common ground, but different capacitive and inductive elements.

[0051] Figure 7 illustrates a multimode antenna with shared inductances L_1 and L_2. and discrete capacitances C_1, C_2, and C_3. The antenna comprises several antenna elements.

[0052] One embodiment of the present invention relates to an antenna with the radiating elements and the conductor lying in substantially the same plane. The radiating elements and the planar element have a thickness that is much less then either their length or width; thus they are essentially two dimensional in nature. Preferably the antenna structure is affixed to a substrate. Figure 8 illustrates an antenna 10 in accordance with the principles of the present invention that is formed flat on a substrate 12. The antenna is substantially two-dimensional in nature. The antenna comprises a planar conductor 14, a first parallel elongated conductor 16, and a second parallel elongated conductor 18. The planar conductor is positioned in the same plane as the electric field, known as the E-plane. The E-plane of a linearly polarized antenna contains the electric field vector of the antenna and the direction of maximum radiation. The E-plane is orthogonal to the H-plane, i.e. the plane containing the magnetic field. For a linearly polarized antenna, the H-plane contains the magnetic field vector and the direction of maximum radiation. Each of elongated conductors 16 and 18 are electrically connected to the planar conductor 14 by respective connecting conductors 20 and 22. Antenna 10 comprises elongated conductors 16 and 18 that are in the same or substantially the

same plane as the planar conductor 14. The gap between the elongated conductor 16 and the elongated conductor 18 is the region of capacitance. The gap between the elongated conductor 16 and the planar conductor 14 is the region of inductance. In a preferred embodiment, the space between the first elongated conductor 16 and the second elongated conductor 18 is much less than the space between the first elongated conductor 16 and the planar conductor 14.

[0053] In an alternative embodiment, shown in Figure 9, the radiating element and the conductor may be isolated. In Figure 9, a grounded planar conductor 32 is isolated from a radiating element 30 by an etched area 34. An antenna feed 36 is supplied and a return for the ground 38 is supplied. The antenna feeds 36, or feed lines, are transmission lines of assorted types that are used to route RF power from a transmitter to an antenna, or from an antenna to a receiver. In accordance with the principles of the present invention any of the antenna structures discussed herein could utilize an etched area or other means to isolate the radiating element or elements.

[0054] Another embodiment of the present invention relates to the use of the antenna structure previously described having an essentially two-dimensional structure, in combination with another planar conductor. The second planar conductor may be located on a opposite face of the substrate. Preferably, the two planar conductors are substantially parallel to eachother. Figures 10A-10C show an antenna 40 with planar conductors 44 and 46 on opposite sides of the substrate 42. Vias 50 and 52 provide the antenna feed and shorts to ground, respectively. The vias 50 and 52 connect the radiating elements to the planar conductor 46.

[0055] In another embodiment, the antenna structure may utilize more than one radiating element. The radiating elements may be arranged side-by-side as showing in Figures 11A-11C. Figures 11A-11C show a dual frequency antenna structure,

similar to the single element structure of Figures 10A-10C The antenna structure has radiating elements 60 and 62 arranged side-by-side. Each radiating element has vias connecting the radiating element to the planar conductor on the opposite face of the substrate. The planar conductors are substantially parallel to eachother.

[0056] Alternatively, the radiating structures may be placed in a nested configuration as shown in Figure 12. Figure 12 shows another dual frequency arrangement implementing the design of Figure 6 on a substrate in a manner similar to Figure 8. In yet another embodiment of the present invention, the antenna structure may utilize three or more radiating elements. The radiating elements may all be located on the same face as the planar conductor. Figure 13 shows an antenna structure similar to that of Figure 12, but with an additional conductor 70 to increase the frequency diversity.

[0057] Figures 14A-14B show an antenna structure on a substrate 80. Face A of substrate 80 carries a three frequency antenna structure as shown in Figure 13. Face B of substrate 80 carries a single frequency antenna structure as shown in Figure 8, although alternatively this could also be a multifrequency structure or any combination of single and multifrequency structures.

[0058] In an another embodiment, the antenna structure may comprise conductors on any of the faces of the substrate. The conductors may be located in parallel and opposite arrangements or asymmetrically. Figures 15A-15B show an antenna structure 90 with conductors formed, such as by conventional printed circuit methods, on the edges as well as the face surface of the substrate 92. This allows even more space savings in certain packaging configurations.

[0059] In yet another embodiment, more than one substrate may be used. As shown in Figures 16A-16B, an second substrate bearing additional conductors can be utilized. The second substrate may be located perpendicular to the first substrate. As shown in Figures 16A-16B, a primary substrate 100 carries a

multifrequency antenna structure, such as the one shown in Fig. 13. A secondary substrate 102 is mounted substantially perpendicular to the primary substrate. The substrate 102 carries a single frequency antenna structure, although alternatively this too could be a multifrequency structure.

[0060] In addition, in accordance with the principles of the present invention more than one secondary substrate may be utilized. Figures 17A-17B show additional arrangements, similar to Figures 16A-16B, wherein a plurality of secondary substrates, each carrying respective antenna structures, are mounted on a primary substrate.

[0061] Furthermore, the secondary substrate may be arranged in any configuration, not only in perpendicular positions. Figure 18 illustrates an antenna 110 on a substrate 112 that is extended relative to substrate 114. This allows installation of the antenna in an enclosure with a shape that just allows an antenna along the side of the enclosure.

[0062] Figure 19 illustrates a configuration similar to that of Figure 18, but with two antennas for frequency diversity.

[0063] An antenna structure in accordance with the principles of the present invention may be integrated into an electronic device. The previously discussed benefits of the present invention make such an antenna structure well suited to use in small electronic devices, for example, but not limited to mobile telephones. Figure 20 shows the antenna structure of Figure 19 housed within an enclosure, such as the case of a mobile telephone or other electronic device.

[0064] Figure 21 illustrates a configuration similar to that of Figure 19, but with four radiating elements, including elements carried on secondary substrates 120 and 122.

[0065] Figure 22 shows the antenna structure of Figure 21 housed within an enclosure, such as the case of a mobile telephone or other electronic device. The

low profile of the antenna of the present invention allows for the antenna to be placed easily within electronic devices without requiring a specifically dedicated volume.

[0066] Figure 23 illustrates a circuit board 130 with radiating elements 132 and 134 disposed at opposite ends thereof. Similarly, in Figure 24, an electronic device, such as a laptop computer 140, is configured with a plurality of radiating elements. Owing to their construction, the radiating elements may be arranged within the computer wherever space is available. Thus, the design of the computer housing need not be dictated by the antenna requirements.

[0067] In yet another alternative embodiment, the antenna structure may comprise grooves. The grooves may be partially or completely through the substrate in various locations, such as between the radiating elements. Figure 25 illustrates an antenna of the type generally shown in Figure 9. The antenna is formed, such as by conventional printed circuit techniques, on a substrate 150. A groove 152 is milled partially or completely through the substrate in the capacitive region of the antenna to improve the efficiency of the antenna.

[0068] Figure 26 illustrates the same concept shown in Figure 25, but in the case of a multifrequency antenna. Here, a plurality of grooves 162 are milled into substrate 160 between each pair of radiating conductors.

[0069] The antenna structures in accordance with the principles of the present invention may be made by any means known in the art such as the use of traditional circuit printing. Figure 27 illustrates an alternative method for fabricating an antenna in accordance with the present invention. Rather than etching the antenna pattern on a printed circuit board, here the antenna is etched on a metallic film that is then molded in plastic. The resulting structure may be attached in various ways to a circuit board or to a device enclosure.

[0070] Accordingly, while embodiments and implementations of the invention have been shown and described, it should be apparent that many more embodiments and implementations are within the scope of the invention. Therefore, the invention is not to be restricted, except in light of the claims and their equivalents.